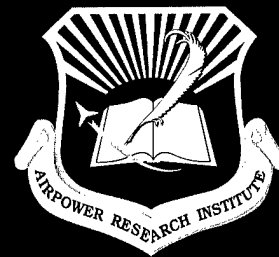


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Technology Challenges for Operationally Responsive Spacelift

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Executive Summary

Space has become a critical part of the United States' warfighting capability and requires that future space systems become more responsive than the current systems of reusable and expendable launch vehicles. The US military relies on space assets for communication, navigation, and intelligence, surveillance, and reconnaissance. Our adversaries also recognize our reliance on space technology and are moving forward to deny us the use of those systems. To reduce our vulnerability to those threats, the United States must have the ability to responsively replace, supplement, and service its space assets. Although the development and operational use of systems that will support the evolving mission areas of space control and force application will be subject to political and fiscal leadership decisions, they will also require responsive spacelift capabilities and it is prudent to include those considerations in spacelift planning.

An analysis was begun in March 2003 to look at alternative affordable launch-vehicle systems and determine if one of those could satisfy all the requirements of the various missions. That analysis was subsequently expanded to incorporate the unique requirements associated with responsive payloads, but excluded most alternatives that incorporated advanced technologies, allowing only those systems that were needed to meet the requirements and for which the associated risks were thoroughly understood. That constraint reflected the historical observation that the root cause of most cost and schedule overruns was the premature incorporation of new technology in systems and programs.

The National Aeronautics and Space Administration (NASA) has a similar need for an advanced launch vehicle system to support the international space station and provide technology development in support the US commercial space industry. Over the last decade, they have conducted research and developed prototypes to better define a replacement for the space shuttle system, but nothing has met their cost savings expectations or operational goals. NASA's Next Generation Launch Technology (NGLT) program was specifically designed to identify and develop critical technologies for potential use in a reusable launch vehicle system. Although NASA may not see the need for a reusable launch vehicle as it embarks upon the president's space exploration vision, many, if not most, of the technologies that NASA might incorporate into a future launch vehicle could also be used in an Air Force system.

Table of Contents

	<i>Page</i>
EXECUTIVE SUMMARY	i
LIST OF ILLUSTRATIONS.....	iii
CHAPTER 1: TECHNOLOGY CHALLENGES FOR OPERATIONALLY RESPONSIVE SPACE	1
CHAPTER 2: MISSION NEEDS AND CONCEPTS OF OPERATION	5
CHAPTER 3: LAUNCH VEHICLE ALTERNATIVES	9
Major Launch Vehicle Architecture Decisions	10
Launch Vehicle Architecture Descriptions.....	13
Horizontal Takeoff, Horizontal Landing	13
Vertical Takeoff, Horizontal Landing Architecture	15
Responsive Expendable Launch Vehicle	16
Partially Reusable Launch Vehicle.....	17
Two-Stage Hypersonic Launch Vehicle.....	18
CHAPTER 4: PRIMARY TECHNOLOGY CHALLENGES	21
Propulsion System Background and Challenges	21
Aero-structural Challenges	25
Avionics Challenges	27
Mechanical and Electrical Challenges.....	28
Operations and Payload Challenges	29
CHAPTER 5: THE WAY AHEAD.....	31
CHAPTER 6: CONCLUSIONS	35
GLOSSARY	37

List of Illustrations

	<i>Page</i>
Figure 1. NASA technology readiness level chart.....	10
Figure 2. A portion of a Launch vehicle's architecture decision tree	11
Figure 3. Gryphon HTHL TSTO launch vehicle concept.....	14
Figure 4. Gryphon Integration Operations.....	14
Figure 5. Space Transportation System, with space shuttle Discovery	15
Figure 6. VTHL TSTO concept.....	16
Figure 7. Responsive Expendable Launch Vehicle	17
Figure 8. TSTO Hypersonic Launch Vehicle	18
Figure 9. Shaft horsepower to weight comparison: High thrust-to-weight rocket engines compared to aircraft and automotive engines, courtesy of Dr. Robert Swinghammer and provided by Mr. Bob Sackheim, assistant to center director for propulsion, NASA Marshall Space Flight Center, AL.	22
Figure 10. CAIB testing of RCC wing panel, courtesy of the <i>Columbia</i> Accident Investigation Board website, http://www.caib.us/photos/	27
Figure 11. Space shuttle thermal protection system materials, courtesy of the CAIB website.....	27
Figure 12. Three-pillars of the National Aerospace Initiative	32

Chapter 1

Technology Challenges for Operationally Responsive Space

Technology-to-warfighting is a key to our third core competency—integrating operations.

—Gen John P. Jumper
CHIEF's Sight Picture, 17 July 2003

Operationally responsive space will provide the warfighter with transformational capabilities by providing responsive space asset delivery and servicing to, from, and through space. During the last few years, the United States Air Force Space Command (AFSPC) has been conducting studies to define the mission needs and concepts of operation for Operationally Responsive Spacelift. That program was broadened to include responsive payloads in 2003 and then renamed operationally responsive space, both using the acronym ORS. AFSPC is currently conducting an analysis of alternatives (AoA), scheduled for completion in 2004, to determine whether a launch vehicle system and payloads to meet the ORS mission needs are cost effective. The AoA is evaluating the entire spectrum of potential launch vehicle architectures, including expendable, reusable, and partially reusable launch vehicle systems. The ORS AoA is also evaluating the types of payloads and the associated military utility. The selected ORS launch vehicle architecture will either take advantage of existing technologies in a new manner or require new technologies, both thereby affecting development risk. Development risk challenges—on-schedule and on-budget performance. In the future, there will be only two types of programs—those that are within budget and those that are cancelled, so the technical challenges must be thoroughly understood before beginning an ORS system development.

In a recent interview, Gen Lance W. Lord, AFSPC commander, stated “the spacelift capability we choose based on the results of our operationally responsive spacelift (ORS) AoA might turn out to be a reusable military space plane. It could also turn out to be a new generation of expendable boosters or in some other fashion. The goal is to find the best way to achieve a particular warfighting effect and that will dictate the specific technology or system we pursue.”¹ Currently the US military relies upon a fleet of expendable launch vehicles for its access to space. After the space shuttle *Challenger* accident in 1986, the US military decided it would not rely upon the space shuttle and eventually began development of the evolved expendable launch vehicle (EELV) program, producing the Atlas V and Delta IV launch vehicles that made initial flights in 2002. The EELV program was developed to modernize the Air Force's space launch

capability, while increasing the cost effectiveness and operational responsiveness. The February 2003 space shuttle *Columbia* accident did not affect the US military's access to space, but it highlights the need for a more responsive access to space.²

Under Secretary of the Air Force Peter B. Teets, testifying before Congress, said that "our EELVs are the best expendable launch vehicles the world has ever seen, but they still lack the responsiveness necessary to ensure our ability to rapidly replenish critical on-orbit capabilities. Today we still talk about time on the launch pad in terms of weeks, perhaps months, to prepare a satellite for launch. If we intend to have operationally responsive assured access to space, we need to find ways to bring that cycle time from weeks and months down to hours and days."³ The EELVs are designed to address many of the operational problems that have plagued their legacy systems, and the Atlas V recently demonstrated a 24-hour turnaround (pad to launch processing building and back to the pad) to replace a faulty avionics unit. However, the EELVs were not designed for the sortie rates and response times that may be needed in the future.

A system developed to provide operationally responsive space must ensure it provides the capabilities to generate the warfighter's desired effects. One of the most important questions is whether the operational responsiveness requirement is on the order of hours or days. The answer to that question could greatly affect the systems development cost and risk. Any potential ORS program must not be one to build the perfect space launch vehicle that technologists can envision—it must be derived from requirements through a rigorous evaluation of alternatives, or trade-off studies. The evaluation must also be iterative; to ensure the selected system doesn't require too much technology development, the process must allow a pushback against the requirements to obtain the optimum system. Further, as General Jumper said, "(w)e must get out of the mode of thinking only in terms of platform rather than in terms of capabilities. The time will come when we no longer have platforms dedicated to a single role or mission. Platforms must be capable of delivering capabilities."⁴

Speaking on the need for new technology, NASA's administrator Sean O'Keefe commented: "(s)ince the Wright brothers' historic flight nearly 100 years ago, our technology has evolved from simple internal combustion engines to jets; from subsonic to supersonic aircraft; and from crude rockets to the space shuttle. Each advance represents an amazing story of the 20th Century. However, as we move forward into the 21st Century, we find ourselves at a crossroads. We have gone as far as we can with current technology. If we are to overcome the limitations of human space travel and open new frontiers for exploration, we need new advances."⁵ While this statement obviously addresses human space flight and exploration, the same theme applies to military use of space.

ORS technology challenges are not as daunting as the ones for human space exploration that Mr. O'Keefe references. The technology challenges for developing a responsive military space launch vehicle might better be defined as areas where the vehicle systems and components must be improved to reduce the development risk. No significant inventions or break-throughs in physics are needed; the challenges lie primarily in the design and manufacturing implementation to meet the mission requirements.

In order for us to understand the technical challenges facing the development of an ORS system, it is helpful to review the mission needs and concepts of operations (CONOPS), the alternative launch vehicle architecture concepts and their significant enabling or limiting technologies at the architecture level. Technology has been the key to a transformation on the battlefield, the speed and precision of operations over the last few years has demonstrated this. Finally, a discussion of the significant technical challenges is relevant.

Notes

1. Gen Lance Lord, AFSPC Commander, interview with Military Aerospace Technology Online, "Leading Air Force Space Command in the 21st Century," http://www.military-aerospace-technology.com/features/2_1_QA.cfm.
2. If NASA or the Air Force had the ability to send supplies to the Columbia in orbit the outcome might have been different. The Columbia Accident Investigation Board report concluded that although the NASA Mission Management Team believed that if significant thermal protection system damage was found—using national assets—there was nothing that could be done; however, the board found that it might have been possible, using another space shuttle, to launch a high-risk rescue mission within 30 days. If a responsive spacelift system had existed with the envisioned capabilities, it might have played a critical role in such a rescue attempt.
3. House, Statement by the Honorable Peter B. Teets, under secretary of the Air Force, before the Subcommittee on Strategic Forces, House Armed Service Committee, 108th Cong., 2d sess., 19 March 2003, <http://www.house.gov/hasc/openingstatementsandpressreleases/108thcongress/03-03-19teets.html>.
4. Gen John P. Jumper, "Technology-to-Warfighting: Delivering Advantages to Airmen," CHIEF's Sight Picture, 17 July 2003, http://www.af.mil/media/viewpoints/Technology_to_Warfighting1.pdf.
5. Sean O'Keefe, administrator, National Aeronautics and Space Administration, National Aerospace Initiative website home page, <http://www.dod.mil/ddre/nai/>.

Chapter 2

Mission Needs and Concepts of Operation

Operationally Responsive Space (ORS), the Air Force finds, is the key enabler for achieving space superiority and conducting the full spectrum of military operations in space. ORS involves two subtasks. The first is transporting mission assets to, through, and from space. This task encompasses the spacelift missions of delivering payloads to and/or from mission orbit and changing the orbit of existing systems to better satisfy new mission requirements. It also supports emerging missions like space control, missile defense, and force application. ORS must be available on demand, flexible, and cost effective. Spacecraft servicing, the second subtask, encompasses traditional satellite activities, but also includes resupply, repair, replacement, and upgrade of space assets while in orbit. "Mission priority, cost tradeoffs, and technological advances will dictate the method for accomplishing these objectives."¹

Achieving those objectives requires four key capabilities: on-demand satellite deployment to augment and quickly replenish constellations; launch to sustain required constellations for peacetime operations; recoverable, rapid-response transport to, through, and from space; and integrated space operations mission planning to provide near real time automated planning to enable on-demand execution of space operations.²

Col Henry Baird, deputy director for requirements at AFSPC, said that "space launches will likely continue to be reserved for special purposes. . . Their flight rate may be more similar to the service's use of B-2 stealth bombers than its use of fighter jets."³ This analogy provides a reasonable reference upon which system requirements can be developed, with the alert operations of Strategic Air Command (SAC) aircraft providing further historical context.⁴ However, since space launch vehicles use rocket propulsion and aircraft use gas turbine engines, each have inherently different operational requirements and, therefore, the concepts of operations and concepts of employment must be developed accordingly. For example, jet engines normally operate at a fraction, normally 20–30 percent of their maximum power rating, whereas most rocket engines operate at 100 percent power for the entire mission. Some of these unique characteristics and requirements have important effects on the launch vehicle and its operations.

Current spacelift responsiveness is driven by the launch vehicle, the satellite readiness, and the vehicle/payload integration; Col Pamela Stewart adds that "responsive space is nothing without responsive payloads."⁵ The high cost of a space launch requires that satellites operate reliably for many years. Those reliability and life requirements have lead to satellite design solutions that have redundant systems and large propellant and power systems—resulting in

large, heavy, expensive satellites. Current satellite designs have also tended to be unique and, as such, are not compatible with the ORS goals. The ORS AoA evaluates payload requirements to derive launch vehicle requirements that will provide the needed military utility.⁶ To meet the mission availability and turnaround time requirements, responsive payloads must have common interfaces and operations, avoiding any specialized or unique aspects. This is true whether the payload is a communication, intelligence, surveillance, and reconnaissance (ISR), or navigation satellite, a space maneuver vehicle for servicing in-space assets, a space-denial system, or a common aero vehicle (CAV) for global strike missions. Payloads must become as easy to integrate into a launch vehicle as bombs are on today's aircraft.

The AoA evaluates the life-cycle costs and risks of each responsive launch vehicle and payload architecture against a series of threat scenarios over a 20–30 year period in a simulation environment. The analysis process consisted of four basic steps.⁷ (1) A military utility analysis (MUA) evaluated the effectiveness of accomplishing mission tasks at low, medium, and high levels of system performance. (2) Responsive-space-system architectures and launch loads were developed and sized to meet these levels of performance. (3) All alternative responsive-launch systems for each of the launch loads were explored. (4) Finally, the most cost-effective launch-system architecture for the defined launch loads for fixed levels of military utility was determined. Determining the fleet size is a classical systems engineering problem. Does the optimum solution have a few highly-capable vehicles that can be prepared for launch, recovered, and turned around quickly, or is it better to rotate more reusable (or partially reusable) less-capable vehicles to accomplish the mission. Although that decision has not yet been made, it will be difficult for a fully expendable system to be as cost effective as a partially/fully reusable system for the anticipated sortie rates.

The MUA preliminarily concludes that "ORS can provide significant military utility at the campaign level," through the use of responsive space asset delivery.⁸ The largest impact occurs when the enemy has offensive counterspace (OCS) capabilities, and responsive launch vehicles and satellite systems are used to maintain on-orbit capabilities. Force application (FA) and OCS missions also provide significant military utility, with the FA contribution increasing as a function of theater access.⁹

The *call-up time*, defined as the time required to prepare the vehicle for launch, and the time required to launch the vehicle significantly influences the technology challenges.¹⁰ The only operational reusable launch vehicle, the space shuttle, has barely approached a one-flight per month rate.¹¹ The space shuttle main engines (SSME) require an extensive amount of maintenance and inspection between missions, and due to the design of the aft compartment, it is often more convenient to remove the main engines after each flight to gain access to other systems. Also, as confirmed by the space shuttle *Columbia* accident, foam separating from the external tank during launch has routinely damaged the tiles of the orbiter's thermal protection system, requiring maintenance and repair. A responsive launch vehicle requires a design that avoids or solves these types of issues. Additionally, the contingency call-up and launch time requirements must be examined with respect to decision timelines and operational flow. For example, the responsiveness of a precision strike on a time-critical leadership target using a precision-guided munition from a CAV will be shorter than delivering a tactical satellite, and that, in turn, will be shorter than on-orbit servicing of a communication or navigation satellite.

Although due to the unique militarily nature of these missions a blue-suit operation is envisioned, the use of either contractor personnel or a military/contractor combination may also be attractive. The architecture must be compatible with Air Force personnel operating the system, accommodating the training, safety, and personnel turnover issues. For example, the selection of launch-vehicle propellants is greatly influenced by the assumptions about the knowledge, skill, and experience of the operations personnel, requiring close coordination between architecture and manpower planners and the use of accurate manpower assumptions.¹²

Operational training needs to sufficiently simulate the wartime surge mode to develop confidence in operations; again, looking very similar to a SAC B-52 emergency war order (EWO) exercise during the 1980s. This type of training will be very expensive if actual launches are conducted. For a reusable vehicle, one of the primary exercise objectives would be to demonstrate the turnaround capability and understand the unplanned maintenance. Conducting actual launches may be necessary at least once per year. With proper planning, these exercises could be a win-win, achieving critical training, conducting new systems tests, and deploying required space assets.

Continental United States (CONUS) basing and infrastructure are assumed for the operational ORS system. Initial operations and testing would take place at the existing launch facilities and test ranges at Cape Canaveral AFS, Florida and Vandenberg AFB, California. However, those launch sites' physical and operational security issues may require locating the system further inland. Selection of a permanent basing location, or multiple locations, is influenced by the operational requirements of the system itself, primarily the payload mass and orbital inclination requirements. Other significant factors include access to propellants, transportation, weather conditions, overflight of populated areas, and abort recovery locations. The locations of launch sites have historically reflected public safety considerations, minimizing the consequences of the catastrophic failure of a vehicle or a range-safety officer's commanded-destruction of a rocket. Those concerns resulted in launch locations in relatively remote coastal regions. Obviously, the public safety risks from expended-stages of launch vehicles falling into populated areas or launch-vehicle failures were minor considerations for locating ICBM launch facilities during the Cold War. The commercial launch vehicle studies of the late 1990s, including NASA's X-33 and X-34 programs, and Lockheed Martin's commercial Venture Star single-stage-to-orbit (SSTO) system made substantial progress in understanding the risk to the public from reusable launch vehicles. In fact, commercial spaceports from inland CONUS states, including Texas, Oklahoma, and New Mexico solicited Lockheed Martin for the Venture Star base.¹³ The assumption being developed was that a reusable launch vehicle could be made reliable enough that the risk to the public would be similar to that of commercial aircraft. The space shuttle *Columbia* accident and the debris-field from its break-up during reentry should provide lessons for future reusable launch vehicle (RLV) systems.¹⁴

Weather is a critical factor in the launch availability of the space shuttle fleet, constraints for winds, cloud cover, rain, and cold temperatures at the launch pad and the abort recovery runways have caused many launch and landing delays. Similar conditions have delayed the expendable launch vehicle fleet through the years, but they are somewhat more robust. The new system should be designed and technologies identified to enable launch and recovery under a greater range of weather conditions.

Notes

1. Mission Need Statement AFSPC 001-01, for Operationally Responsive Spacelift, 20 December 2001.
2. Ibid.
3. Jeremy Singer, "US Air Force Sees Quick and Frequent Launches in its Future," *Space News*, 14 July 03, http://www.space.com/spacenews/spacenews_businessmonday_030714a.html.
4. SAC strategic aircraft operations are probably a much better point of departure than SAC strategic missile operations.
5. Col Pamela Stewart, study director at HQ AFSPC, interview by the author, 12 December 2003.
6. Leonard David, "Air Force to Focus on Quick Reaction Spacelift Vehicles," *Space.Com*, posted 28 March 2003, http://www.space.com/business/technology/technology/af_space_030328.html.
7. Col Pamela Stewart, AFSPC Operationally Responsive Spacelift (ORS) Analysis of Alternatives (AoA) Interim Status Brief, 2003 Core Technologies for Space Systems Conference, Colorado Springs, CO, 4 Nov 2003.
8. Ibid.
9. Ibid.
10. The *call-up time* is the time interval required to bring the vehicle from its normal standby status, integrate the payload, transport it to the launch facility, and prepare it for prelaunch operations and propellant loading.
11. NASA achieved rates of 8–10 flights per year during the late 1990s, while they had four Space Shuttle Orbiters. Since one orbiter was usually in depot-level overhaul for upgrades, the turn-around time was on the order of 3–4 months.
12. Air Force operations and maintenance crews have repeatedly demonstrated their ability to work with hazardous propellants and pyrotechnic devices routinely and safely.
13. The Oklahoma Spaceport, located at the former Clinton-Sherman AFB at Burns Flat, Oklahoma, has been chosen by Rocketplane, for its commercial space tourism business. Rocketplane plans to offer suborbital spaceflights to 100 km by 2007. Although this area of mostly farm and ranch land has a relatively low population density, it is much higher than other areas of the western United States, indicating that the public safety risk is being quantified as being sufficiently low to obtain insurance coverage.
14. Columbia Accident Investigation Board, "Report of Columbia Accident Investigation Board," vol. 1, August 2003 (Washington, DC: Government Printing Office), chap. 10. This report details the significant findings and recommendations relating to public safety and risk due to reentry orbital debris. Finding F10.1-2 is particularly interesting, "Given the best information available to date, a formal risk analysis sponsored by the Board found that the lack of general-public casualties from Columbia's breakup was the expected outcome." This finding indicates that the orbital debris risk assessment methods are credible.

Chapter 3

Launch Vehicle Alternatives

Selection of the launch vehicle architecture for responsive spacelift is a difficult, iterative process that seeks to maximize the military utility, as judged by its mission effectiveness and affordability. There is never a single best solution; it is always a function of the relative importance given to the technical performance measures. For example, a system that might provide a four-hour call up, two-hour launch preparation, and two-hour turnaround may require several billion dollars more and several more years of development time than a system that can be developed immediately, but requires 24-hour call up, eight-hour launch preparation, and 48-hour turnaround time. Designing a military aircraft is an easier process, once the mission of the aircraft (fighter, fighter/attack, bomber, cargo, etc.) and its requirements are known. The architecture of military aircraft is relatively straightforward because there is not that many different ways to design airplanes. For example, all fighter aircraft look somewhat similar and have similar type systems but the challenges reside in the detailed design decisions to maximize the plane's functionality. For an access-to-space launch vehicle, the technical literature is filled with various ways to punch through the dense atmosphere and climb out of earth's gravity into orbit. Concepts ranging from multistage expendable rockets that look similar to the first rockets that placed satellites in orbit over 45 years ago, to single-stage aerospace planes that are still more science fiction than science fact, are alternatives for consideration. Specifically, because there is not a single definitive solution for putting payloads into low earth orbit, the development of new and unique space transportation architectures and revisiting old concepts are constant topics at domestic and international aerospace conferences.

The space shuttle, the world's only operational reusable launch vehicle, was originally intended to be much more responsive than its operations have demonstrated.¹ The original planning anticipated up to 40 flights per year. The late inclusion of military payload requirements forced the design of the cargo bay to carry larger and heavier satellites, and administration budget pressures resulted in a design with lower initial development cost, but significantly higher maintenance being required between flights. During the last 10-15 years, NASA conducted several design studies to evaluate space shuttle improvements and the development of a new reusable launch vehicle; those ideas were available for the AoA to use.

During the early 1990's, several commercial telecommunications businesses had plans for constellations of telecommunication satellites in low earth orbit. These companies faced a classic *Catch-22* problem. They couldn't offer their communication services at reasonable rates until the cost of the launch services was reduced, but the cost of launch services could not be

reduced until the demand for launch services was established and new launch providers entered the market with less expensive launch services. This potential market encouraged entrepreneurs to develop and build a better launch vehicle. The operational architecture requirements (i.e., payload mass, launch rate, and responsiveness) that the low-cost sector of the commercial space-launch industry were developing were similar to the ORS requirements. Some companies proposed reusable vehicles that would reduce cost by spreading the development cost over hundreds of flights.² Other companies attempted to build simple systems, whose inefficiency and low reliability were compensated for by their ultra-low cost.³ Each of these solutions engaged technology in different ways: some attempted to use advanced manufacturing methods to reduce cost and/or reduce weight, others used technology to increase efficiency, and still others reduced the cost and size of the flight control electronics through the use of commercial off the shelf computers and GPS navigation. The establishment of the terrestrial telecommunication infrastructure of fiber optic cables and cellular phone towers discouraged the development of a low-earth-orbit (LEO) telecommunications satellite delivery market; and, as a result, those low-cost companies have yet to field a launch vehicle.

Major Launch Vehicle Architecture Decisions

All major launch vehicle architecture decisions are a trade-off process. Each launch vehicle system configuration decision brings both its positive and negative attributes with it. Often, one of the significant negative attributes of a configuration is technology maturity. Figure 1 shows the technology readiness level (TRL) definitions that NASA uses to rate technologies. A technology must generally be at or above TRL 6 for it to be included in a new spacecraft or aerospace system, although it does not exclude newer systems with lower TRLs as long as specific risk mitigation activities are performed to demonstrate its suitability on a similar scale and in an environment equivalent to its new application. The Air Force Research Laboratory has defined two additional terms, *materials readiness level* (MRL) and *process readiness level* (PRL), to further define the maturity of materials and manufacturing process. The *capability readiness level* (CRL) is another term beginning to emerge to describe the tools and processes used during design and development. The purpose of these rating systems is to fully characterize the risk associated with the development of advanced systems and vehicles.

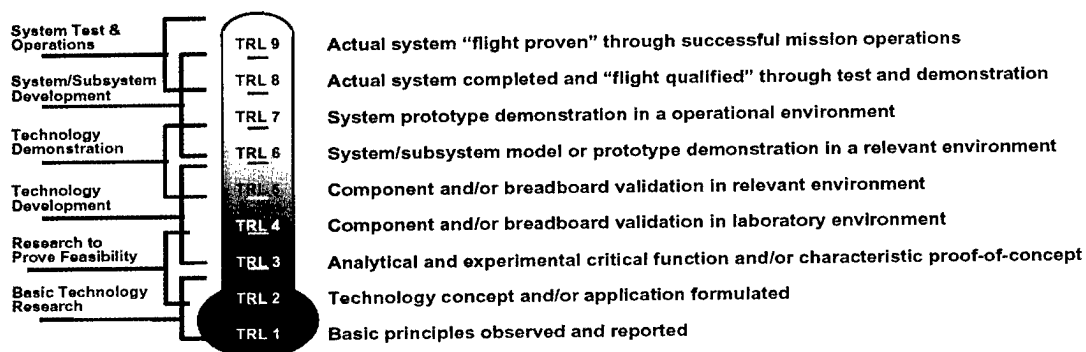


Figure 1. NASA technology readiness level chart

Figure 2 shows a small portion of the launch vehicle architecture configuration decisions that are made when developing a new concept. The decision tree shown represents some of the more important decisions that affect the sizing, operations, and affordability of an access-to-space launch vehicle. For example, the space shuttle architecture consists of delivering 55,000 pounds to a 220 nautical mile (nm) circular orbit with a crew of seven astronauts. It is a partially reusable system; the orbiter was designed for 100 missions, uses reusable liquid oxygen/liquid hydrogen rocket engines, an expendable liquid propellant tank, and partially reusable solid rocket boosters. The system is launched vertically and glides-back for a horizontal, airplane-like landing.

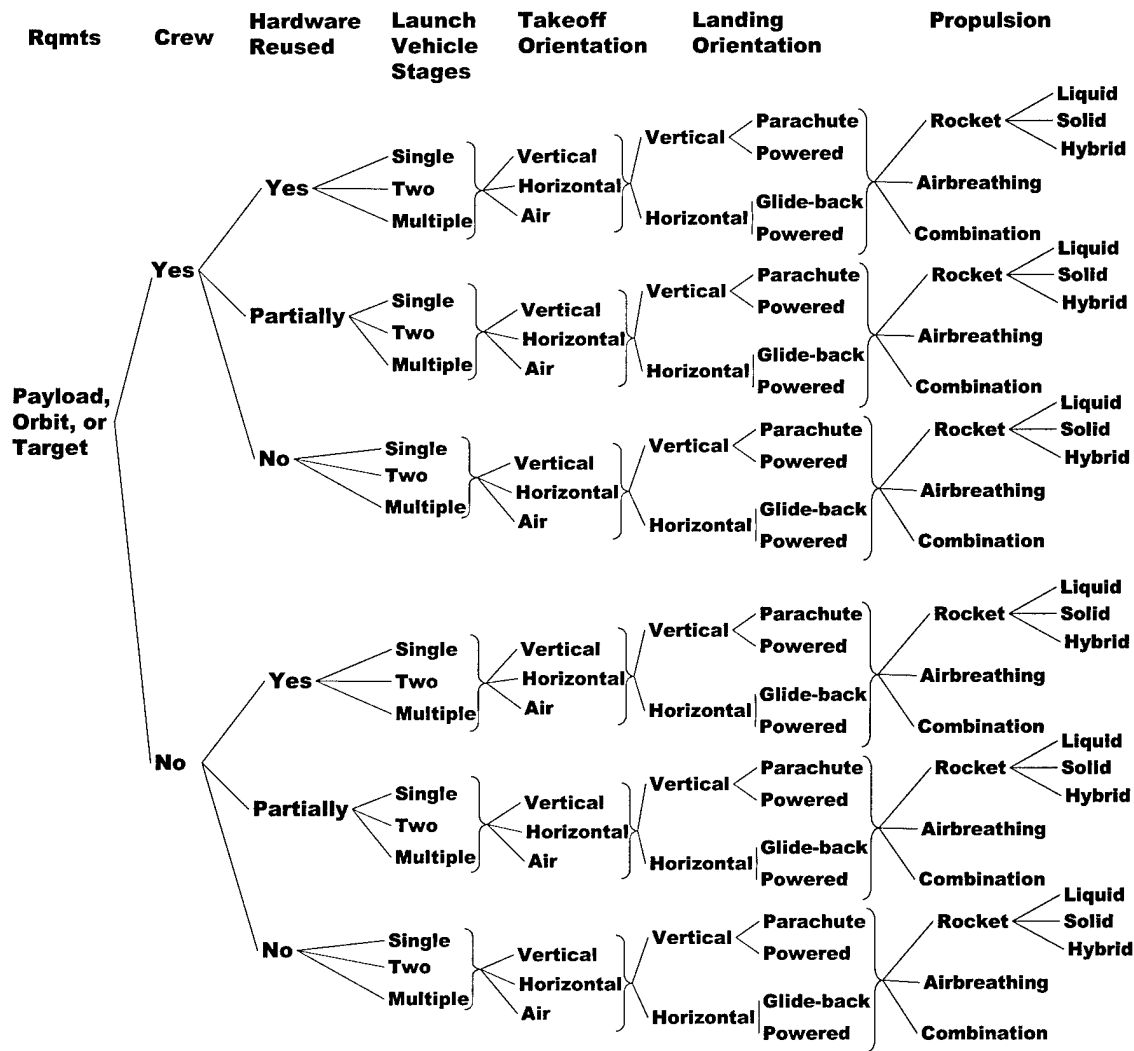


Figure 2. A portion of a Launch vehicle's architecture decision tree

The payload's size and orbital inclination directly effects the launch vehicle size, becoming its are most important design criteria. A responsive military spacelift system will probably be classified as a medium-lift launch vehicle with a payload capacity in the range of 10,000 to 20,000 pounds when launched on easterly trajectory orbits. As a comparison, the space shuttle can deliver up to 55,000 pounds to low earth orbit. Smaller payloads require a smaller launch

vehicle, smaller ground support systems, less propellant, and fewer or smaller systems to inspect and maintain. Thus, they will tend to be more responsive—easier to launch and with a faster turnaround for the next mission.

Another important launch vehicle determinant is whether it will carry a human crew. That requirement increases a launch vehicle's complexity due to the need for flight-critical system redundancy. The mission operations, planning, and logistics must be adjusted to accommodate mission abort from every phase of the mission. The Air Force has determined that an ORS launch vehicle does not require a human crew.⁴ An autonomous operation will provide the most operable system, since the inclusion of a crew would substantially increase the vehicle size and complexity, for the same payload size.

Determining whether the ORS system should be reusable, either wholly or partially, is directly related to the mission requirements and cost constraints. The reusability decision essentially trades a few, robust, complex and expensive vehicles requiring maintenance against cheap, simple, expendable systems. From a technology standpoint, using overly aggressive initial mission requirements (i.e., flight rate, mission availability, call-up time, and turnaround time) significantly increases the development risk, particularly for reusable systems. A fully reusable system will be larger, because it must include additional thermal protection systems, landing systems, and designed structurally for the extreme environment associated with many atmospheric reentries. In contrast, a completely expendable system may be smaller, but must be kept in continuous production to maintain quality and achieve cost efficient operations.

Staging, or the number of launch vehicle segments used to place the payload in orbit, is a fiercely debated issue. The early launch vehicles of the 50's and 60's were all multistage vehicles, with the Saturn V launch vehicle that launched the US's lunar exploration missions having a total of three stages. With conventional rocket engine chemical propulsion, staging is required to reduce the inert mass of the vehicle as it accelerates.⁵ The optimum rocket is one with an infinite number of stages; the structure required for each pound of propellant is jettisoned from the vehicle as that pound of propellant was burned, reducing the remaining mass to be accelerated.⁶ If staging is not used, the vehicle structure must be extremely lightweight and the propulsion system must be incredibly efficient in order for it to accelerate the vehicle's entire mass to orbital velocity. During the mid and late-1990s, NASA focused on developing technologies that would enable single-stage-to-orbit (SSTO) launch vehicles. The X-33 was a suborbital pathfinder project to demonstrate the design and manufacturing technologies for a commercial follow-on orbital vehicle. The X-33 vehicle was not able to demonstrate significant increases in structural efficiency to enable a SSTO vehicle. The project was canceled in 2001 because of project cost overruns. Although rocket-based SSTO vehicles are technically feasible and a single stage vehicle can theoretically reach orbit, using current technology they cannot deliver meaningful payloads without becoming excessively large. Many engineers working on advanced launch-vehicle technology development, including the author, are convinced that rocket-based SSTO architectures and technologies have been and continues to be a poor use of resources.

Multistage launch vehicles can be fully or partially reusable. For example, the space shuttle system is a 1.5 stage system, it uses solid rocket boosters which are recovered and refurbished

for reuse, but the external tank burns up upon atmospheric reentry and falls into the Indian ocean. NASA's Orbital Space Plane (OSP) program is evaluating a concept to transport crews to and from the International Space Station with a reusable crew transfer vehicle on versions of the Delta IV and Atlas V EELV. An ORS launch vehicle could use any combination of expendable and reusable boosters: it could employ a cheap dumb first-stage booster to accelerate a robust reusable second-stage or it could launch with a robust reusable first-stage booster with an expendable second-stage.

Launch Vehicle Architecture Descriptions

Architecture configuration decisions are highly interrelated. This background shows how vehicle architectures can be, and have been, conceptually developed with virtually every combination imaginable. Previous Air Force and NASA architectural concept studies narrow the field of alternatives and a description of some of the more promising architectures will help define the technical challenges for an ORS system.

Horizontal Takeoff, Horizontal Landing

Horizontal takeoff, horizontal landing (HTHL) systems seem attractive because they appear to be essentially airplanes. The primary design challenge for HTHL concepts is constraining the structural-mass fraction—the percentage of the total mass that is made up of structural equipment. If the HTHL aircraft carries all of the propellants, the landing gear and wing sizing must accommodate it and becomes large and heavy. The first of two options proposed to avoid this issue is the vehicle that initially takes off without the rocket engine oxidizer, and the second achieves its initial take-off speed employing a ground acceleration system.⁷ Vehicle concepts that don't use either of these two options get prohibitively large and/or have little payload capability.

Andrews Space Inc. created a concept it calls Gryphon (fig. 3), one of the few uniquely new space-launch vehicle development ideas in many years. Gryphon was studied as part of NASA's Space Launch Initiative program and continues to be evaluated in its NGLT program. This is a two-stage-to-orbit reusable launch-vehicle system that generates its rocket engine's liquid-oxygen oxidizer during subsonic cruise at 20,000 ft. It takes off from a standard heavy aircraft runway using advanced turbofan engines. The Andrews' Air Collection and Enrichment System (ACES) extracts high-pressure bypass air from the turbofan engines, cools and condenses it into a liquid, and then separates the oxygen from the nitrogen.⁸ The oxygen is transferred to the propellant tanks, while the nitrogen is used as coolant for the incoming air and put back into the turbofan engines. The oxygen collection phase takes one to three hours, allowing the aircraft to fly to a launch point away from populated areas and achieve any orbit inclination. The rocket engines are then started and the vehicle climbs to over 200,000 feet, at which point the second-stage is separates and accelerates to orbit. The second-stage could also be used to lob a CAV through a transatmospheric trajectory to a target. The first-stage then reenters the atmosphere, restarts the jet engines, and returns to base under powered flight. When the mission is complete, the second-stage reenters the atmosphere and glides back to a runway landing.

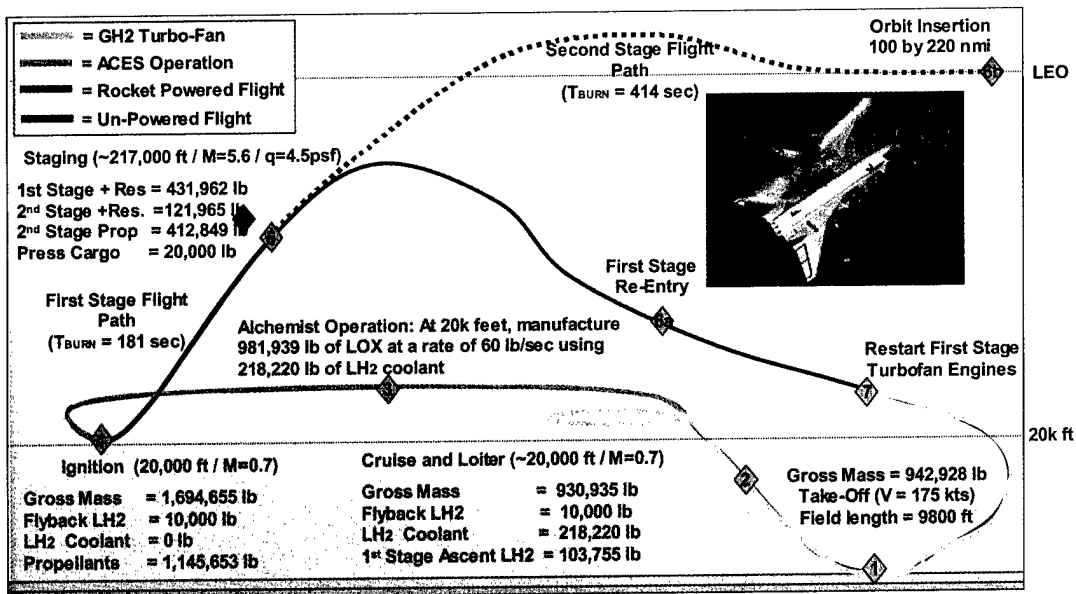


Figure 3. Gryphon HTHL TSTO launch vehicle concept

The Gryphon concept has potential for the ORS mission, depending upon the final definition of “operationally responsive.” This concept could not be as responsive as other systems for a time-critical global strike mission because of the time required to produce the rocket engine oxidizer. That response delay could be reduced if the vehicle was launched in advance of the mission’s final execution order. One could even imagine scenarios where the perceived saber rattling of such a launch could create the desired coercive effect, achieving national objectives without an actual strike. In most cases, however, launching such a high-value asset without a definite execution order is not desirable because it not only puts the system in jeopardy but also risks the delay of having to recover and regenerate the system prior to being able to execute a strike.

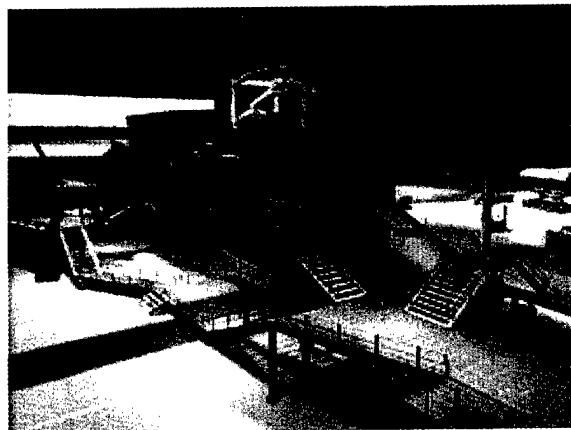


Figure 4. Gryphon Integration Operations

This concept is relatively new and the risks associated with its development are not completely quantified.⁹ The concept is most efficient when it uses liquid hydrogen for the rocket engine fuel since it is required in the heat exchanger to condense the high by-pass compressor air. However, hydrogen is a hazardous propellant that requires specialized training and procedures and may not be conducive for a blue-suit operation.¹⁰ The use of kerosene fueled rocket engines has certain advantages but has not been thoroughly investigated. This architecture's primary areas of enabling technology development are:

- 1) Development and integration of the ACES liquid oxygen production system.
- 2) Development of an airfoil that can efficiently cruise during ACES operation and during Mach 5 ascent.
- 3) Long-life cryogenic propellant tanks.
- 4) Development of highly operable liquid rocket engines.
- 5) Development of an Integrated Vehicle Health Management System to continuously monitor vehicle system performance for real-time faults and identification of maintenance requirements.

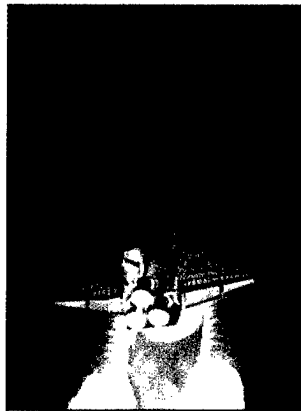


Figure 5. Space Transportation System, with space shuttle Discovery

Vertical Takeoff, Horizontal Landing Architecture

This series of architectures is similar to the Space Transportation System (fig. 5), which includes the space shuttle. It lifts off vertically from a launch pad and after atmospheric reentry it lands on a conventional runway. All current concepts include liquid fueled rocket engines.¹¹ Figure 6 shows a typical TSTO VTHL under consideration, with the payload being carried external to the two-stage vehicle. Both stages are completely reusable, but configurations are feasible with either stage expendable, subject to a life cycle cost trade. Concepts where the engines on both stages burn in parallel and concepts with the engines burning in series have been proposed. Concepts with common and different propellants between the stages have been evaluated, but the most probable choice for an Air Force ORS system would be a vehicle with kerosene fueled liquid rocket engines due to its operational advantages over liquid hydrogen as a fuel.¹² Inclusion of jet engines on booster vehicles is being considered to provide powered flight back to the base. Because the booster vehicle flies back to the launch location, the aerodynamic efficiency of the vehicle is important, the length to diameter ratio of the fuselage, the design of the wing, and mass distribution (center of gravity) of the vehicle must be optimized. Such

vehicles require rocket engines that operate at high pressure, since higher pressure rocket engines can package into a smaller area than lower pressure engines at the same thrust. The primary areas of technology development to enable this architecture are:

- 1) Development of highly operable, high reliability, long-life, oxidizer-rich staged combustion, oxygen/hydrocarbon rocket engines.
- 2) Development of highly operable, high reliability, long-life oxygen/hydrogen rocket engines.
- 3) Autonomous operation control systems.
- 4) Development of highly operable thermal protection systems.
- 5) Gas turbine engines that can air-start during booster vehicle return.
- 6) Long-life cryogenic propellant tanks.
- 7) Development of integrated vehicle health management systems to continuously monitor vehicle system performance for real-time faults and identification of maintenance requirements.

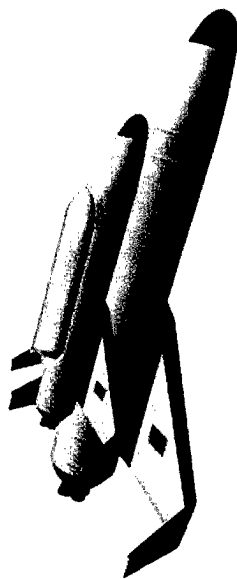


Figure 6. VTHL TSTO concept

Responsive Expendable Launch Vehicle

Inexpensive expendable launch vehicles might have a role in an ORS system, particularly for tactical space warfare missions. The basic concept is the modular combination of simple, easily mass produced stages that can be quickly assembled and launched. Consisting of multiple stages, utilizing simple rocket engines without complicated turbomachinery or high pressure systems, this system would not be as efficient as others, but would make up for it with low cost. Composite materials, due to their high strength to weight ratio, might play an important role. The primary technology challenge for this concept is the ability to mass-produce quality components and systems. Figure 7 shows a potential low cost responsive expendable launch vehicle called the *Sprite Mini-lift* by Microcosm, Inc.¹³



Figure 7. Responsive Expendable Launch Vehicle

This type of system is similar to the systems under development in the Defense Advanced Research Project Agency (DARPA) titled Force Application and Launch from CONUS (FALCON). The FALCON program has multiple contractors attempting to develop a launch vehicle that could deliver a 2,000 lb CAV to anywhere on Earth. A system such as this is essentially a convention weapon intercontinental ballistic missile. Arguably, some of the existing ICBM fleet might be revised and upgraded to meet the mission, however the DARPA objective is to determine if an innovative, lower cost solution can be found from the commercial aerospace industry.

Partially Reusable Launch Vehicle

Combining the most desirable attributes of a reusable system with the most desirable attributes of expendable systems may provide an optimized solution. Assuming a TSTO rocket-based launch vehicle, two obvious solutions exist: an expendable first stage and reusable second stage, and a reusable first stage booster and expendable second stages. The first case might be selected if the primary objective was servicing space systems and having the ability to return them to earth. However, for a high sortie rate, servicing the second stage vehicle to prepare it for launch and mating it with a new expendable booster would not provide the desired responsiveness due to higher maintenance requirements for the orbital spacecraft. In the second case, a reusable first stage booster vehicle becomes a workhorse vehicle carrying the second stage expendable vehicles. With expendable second stages not requiring reentry thermal protection systems or landing systems, wings and landing gear or parachutes, they will be smaller and lighter than a reusable second stage vehicle for the same payload. This option should also provide more flexibility at lower cost. It offers the ability to have a few different expendable upper stage vehicles designed for specific types of missions, for example a second stage for a CAV strike mission, a vehicle for easterly launch LEO satellite delivery missions, a vehicle for higher orbits, and a vehicle for polar orbits.

Two-Stage Hypersonic Launch Vehicle

Vehicles with conventional rocket propulsion carry all of their propellants in on-board tanks, whereas air-breathing engines use the oxygen in the atmosphere as the oxidizer to burn the on-board fuel. Typical launch vehicles are sized to carry the volume and mass of the oxidizer and the fuel. Engineers have sought a way to avoid carrying the oxidizer mass on the vehicle, particularly since that means carrying a large empty tank into orbit. Since the 1960s, researchers have been working on propulsion system designs that operate as advanced aircraft gas turbine engines at low altitudes and as rocket engines at high altitudes for the final thrust needed to reach space. These innovative propulsion systems, called combined cycle engines, are very complicated, operate at extremely demanding operating conditions, and require precise integration with the vehicle. Vehicles using combined cycle propulsion use aerodynamic lift to climb through the atmosphere, so the vehicles must withstand intense aerodynamic forces and heating. If the technologies can be developed to overcome the challenges, such vehicles might be operational in the 2025 timeframe. Figure 8 depicts a TSTO launch vehicle that uses turbine-based combined cycle (TBCC) propulsion on the first-stage, and rocket-based combined cycle (RBCC) propulsion on the second stage. The vehicle takes off from a runway with thrust from an advanced turbo/ram jet and at about the Mach 2-3 range it transitions into a scramjet mode and accelerates to Mach 7+. The second stage separates and operates in scramjet mode until there is no longer sufficient atmosphere to maintain thrust, it then transitions to rocket mode and accelerates to orbit. The primary technology challenges associated with this system include:

- 1) Development of the TBCC and RBCC propulsion systems for high operability and long life.
- 2) Development of advanced aerodynamic surfaces.
- 3) Lightweight, long-life conformal tankage.
- 4) IVHM system for real-time fault detection and maintenance identification.

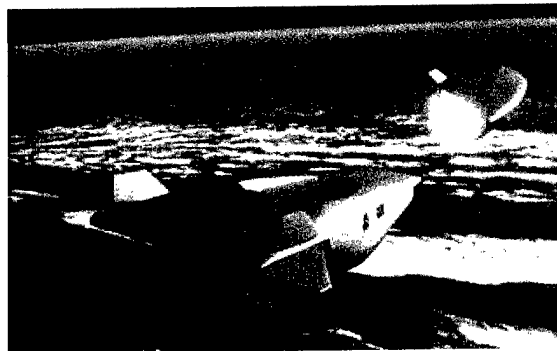


Figure 8. TSTO Hypersonic Launch Vehicle

Notes

1. The Soviet Union built the *Buran*, a reusable launch vehicle modeled after the Space Shuttle. It flew only once as an unmanned test flight. After launch, it completed two orbits, reentered, and landed autonomously. The vehicle was successfully recovered, however it reportedly suffered some reentry heating damage during reentry. The USSR abandoned the program due to limited national resources. The *Buran* is now on display in Gorky Park in Moscow.
2. A notable example is *Pioneer Rocketplane*, whose concept was an aerospace plane that would take off from a runway with turbojet engines, use aerial transfer of liquid oxygen, and then rocket thrust to achieve an altitude sufficient to deploy the second stage with the payload. This concept was a variation of the Blackhorse vehicle presented in the Air Force 2020 study, and former Air Force members of that team founded the company.
3. Microcosm, Inc. is one of the few remaining companies, and has received funding from the Air Force. However, a new group of companies is beginning to emerge.
4. Mission Need Statement, AFSPC 001-01 for Operationally Responsive Spacelift, ACAT Level I, 20 Dec 01.
5. A vehicle's inert mass is determined as the mass of the vehicle and payload minus the mass of the propellant.
6. Bob Sackheim (NASA Marshall Space Flight Center), in discussion with the author, 21 Aug 2003.
7. Architectural concepts of the second type, ground acceleration, are not discussed in this paper.
8. The F135 JSF engine is a potential engine for this application.
9. Although it is made up of technologies that have been in investigation for over 30 years. The ACES process was originally investigated by the Air Force in the 1960s, and for the National Aerospace Plane in the 1980s but for supersonic liquid oxygen production. Subsonic production is more efficient, but requires longer cruise time to fill the oxidizer propellant tanks.
10. Air Force personnel have operated with and around liquid hydrogen systems, but none with the propellant quantities and operational sortie rates envisioned for ORS. Compared with a kerosene-fueled launch vehicle, the propellant loading requirements for liquid hydrogen would reduce its responsiveness.
11. The reliability of solid rocket motors is much less than liquid propellant rocket engines.
12. A discussion of the advantages and disadvantages of liquid hydrogen vs kerosene is later in this paper.
13. Robert F. Conger, Shyama Chakroborty, James R Wertz, and Jack Kulpa, "SCORPIUS, A New Generation of Responsive, Low Cost Expendable Launch Vehicle Family," The World Space Congress 2002, IAF-COSPAR, Houston, TX, October 2002, http://www.smad.com/scorpius/world_paper.pdf.

Chapter 4

Primary Technology Challenges

The primary technology challenges for an operationally responsive launch vehicle lie in the areas of propulsion and aerostructural systems, the development risk in these areas must be mitigated or a viable system cannot be developed. Other technology challenges, in the areas of avionics, power systems, IVHM, mechanical systems, operations, and payloads are essential to meeting the goals and objectives. Some of the technology challenges address shortcomings with our existing system, the space shuttle, while others are needed to obtain additional capabilities. Propulsion systems generally dictate the design of space launch vehicles; development of advanced propulsion systems will enable higher performance vehicles, or in some cases will enable some architectures.

Propulsion System Background and Challenges

Liquid rocket engines and gas turbine engines are fundamentally different types of machines. The power density, cooling requirements, start and shutdown transients, and other operational environments are much more severe in liquid rocket engines. Most engines which we are accustomed to working with on a routine basis are started to a low power level and allowed to "warm-up" prior to being throttled to full-power, usually on the order of minutes. However, rocket engines must start to full-power, on the order of a few seconds, 3-6 seconds on average. This rapid application of severe environments: high pressures, large forces, severe vibrations, and intense temperatures, places tremendous demands on the rocket engine hardware. As a crude example, one would not want to take an iron skillet from the freezer and put it directly into a hot oven without worrying about damage. But that's essentially what happens in a rocket engine, rocket propellant combustion occurs at over 5000 degrees Fahrenheit (°F) and up to 3000 pounds per square inch (psi) pressure in the combustion chamber.

The specific power of advanced rocket engines is much greater than other industrial equipment.¹ Generating and transferring that much power puts tremendous stress on the hardware and it operates at full power for most of its life. While a typical automotive engine or a jet engine are designed to operate for over 100,000,000 seconds (over 3 years), they operate most of their life at low power. Reusable rocket engines are designed to operate for less than 100,000 seconds (slightly over a single day), but operate at full power most of their life. Figure 9 shows a comparison of the specific power for various engines.

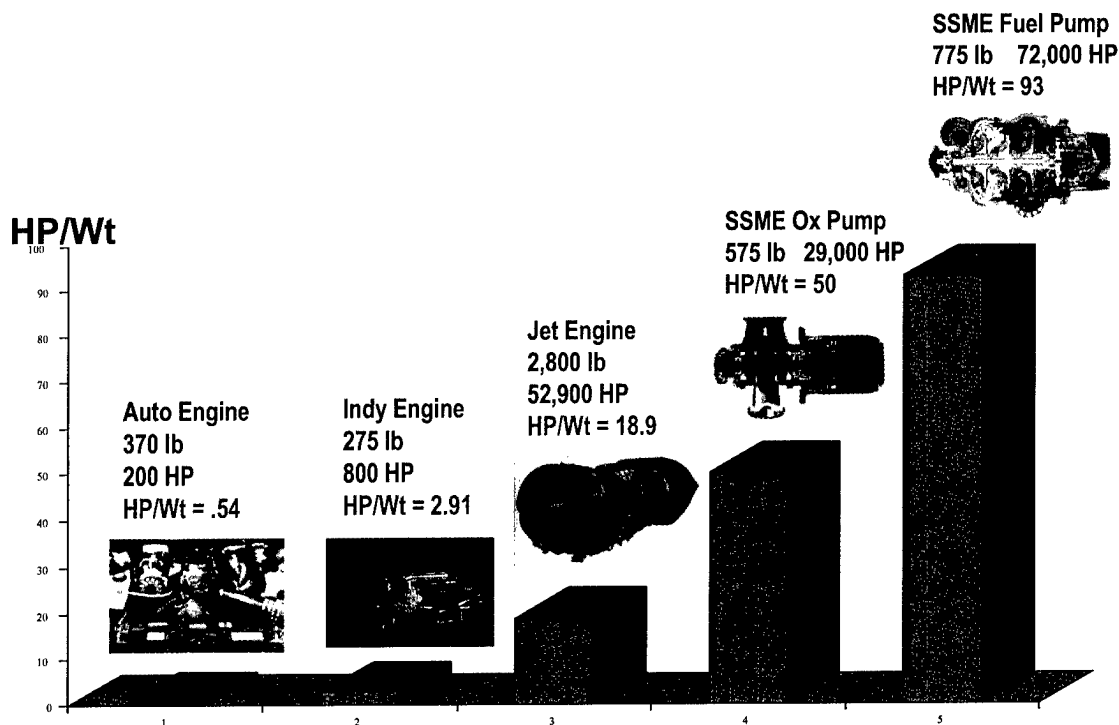


Figure 9. Shaft horsepower to weight comparison: High thrust-to-weight rocket engines compared to aircraft and automotive engines, courtesy of Dr. Robert Swinghammer and provided by Mr. Bob Sackheim, assistant to center director for propulsion, NASA Marshall Space Flight Center, AL.

The selection of propellants is one of the most important decisions for vehicle architectural concepts, it affects all aspects of the vehicle design, operation, and its capabilities. Liquid rocket engines can use liquid hydrogen or hydrocarbon-based fuels, with the hydrocarbon fuels separated into categories of kerosene-based, liquefied petroleums, or toxics. The traditional kerosene-based fuel is Rocket Propellant 1 (RP-1) and has been used extensively since the late fifties. Liquefied petroleums, such as liquid methane or liquid propane, have never been used in an operational system. Toxic hydrocarbons, such as the various forms of hydrazine, have been used extensively, but should be ruled out for an ORS system due to the safety precautions that must be used during its handling.

Liquid hydrogen is an ideal rocket engine fuel because of its excellent cooling capability and the high performance it provides. However, the primary drawback to liquid hydrogen is its low density and extremely low temperature. Liquid hydrogen boils at -423°F , one of the coldest substances on earth. Even as a liquid at -423°F , its density is very low. One pound of liquid hydrogen would almost fill a two-gallon container; by comparison, one pound of water will fit in a one-pint measure. Hence, the hydrogen fuel tank of a medium class launch vehicle (10,000 to 20,000 pounds) is much larger than the oxidizer tank, and the dry weight of the vehicle is more than a hydrocarbon fueled vehicle.

Hydrogen is an extremely flammable fuel that as a gas is colorless and odorless and is ignited with very little energy. Because liquid hydrogen is so cold, its piping must be heavily insulated to prevent air from condensing and creating hazardous liquid air.² Hydrogen (H_2) is the second smallest known atomic element, and because of the small size of the H_2 molecule, it is prone to leakage from storage and piping systems. While Air Force military personnel have historically operated and maintained hydrogen systems, the care and handling that must be exercised with those systems makes them less desirable than other fuel for a highly operable system.

A hydrogen-fueled rocket engine, based on a pound of generated thrust comparison, is approximately 40 percent more expensive to operate, because of the cost of the propellants alone.³ An operational fleet of ORS vehicles will consume immense quantities of propellants, so access to propellants would be a significant issue or the ORS base would require a liquid hydrogen production facility—further complicating the operations. Since, most liquid hydrogen used in the testing and flight of liquid hydrogen rockets engines today is transported by barge or rail, access to rail lines or waterways would become a basing criterion.

The hydrocarbon propellant RP-1 was the fuel used by the F-1 rocket engines on the first-stage of the Saturn V launch vehicle. Since it is a kerosene-based fuel, its handling and operational requirements are similar to the jet fuels used on flight lines today. Using the same volume comparison, a pound of RP-1 would spillover the one-pint measure by about ten percent. The primary technical challenges for using RP-1 in reusable rocket engines are the risk of “coking” in the combustion chamber coolant channels and ensuring that any residual fuel in the engine does not contaminate the oxidizer system. Coking is a phenomenon whereby the kerosene thermally decomposes and deposits form on the inside of the small coolant passages, these deposits cause two detrimental effects. First, the deposit increases the flow resistance in the coolant circuit, and reduces the engine’s performance. Second, the coolant jacket wall temperature increases, which can result in reduced life or a structural failure. NASA and the Air Force Research Laboratory (AFRL) are currently conducting risk reduction activities to quantify the coking phenomena for advanced RP-1 cooled engines, and developing mitigations for those risks.

Liquid methane is another potential fuel, and since it evaporates and does not leave any residue it might address the coking and contamination concerns of RP-1. However, liquid methane is lighter than RP-1 and, since it’s a cryogenic liquid, the vehicle fuel tank would be larger and require thermal insulation to prevent excessive boil-off losses. The handling and operations for a liquid methane fueled vehicle would be more similar to a hydrogen fueled vehicle than to a RP-1 fueled vehicle. Logistically, liquid methane offers a potential advantage. Since methane is the primary component of natural gas, it could be produced at the launch facility by condensing and purifying natural gas from the pipelines. Theoretically, methane offers a performance benefit over RP-1, however that benefit has not been verified in large scale system testing. The primary technical challenge for use of liquid methane as an ORS system rocket engine fuel is to quantify its performance in a large-scale rocket engine system test. On the surface, the potential advantages of methane don’t seem to outweigh its disadvantages—unless the coking and contamination issues associated with RP-1 are not mitigated.

The final selection of a fuel for an ORS system will require development of preliminary design concepts, including ground operations, of sufficient fidelity to evaluate the call-up and turnaround time requirements. The operational constraints imposed by the fuel may play a critical role in determining the capability of some architecture concepts to meet the mission requirements.⁴ This architectural decision highlights the use of the spiral development model of recursive iterations to examine the requirements with respect to their associated challenges and risks.

Liquid rocket engine oxidizers can be separated into two primary classes, cryogenic and storable.⁵ Liquid oxygen is the most common cryogenic liquid oxidizer for rocket engines. Most storable oxidizers are highly toxic, including nitric acid and hydrogen peroxide.⁶ Due to nitric acid's toxicity, it should not be seriously considered because, like hydrogen fuels, it has reduced operability. High concentration hydrogen peroxide is worthy of consideration for some aspects of an ORS system, particularly for use in upper stage and in-space propulsion, however it is very sensitive to contamination and its rapid decomposition can cause explosions. The use of liquid oxygen for an ORS system does not impose any technical challenges.

Existing rocket propulsion systems are inadequate for a reusable responsive spacelift system. The only US rocket engine designed and certified for use in multiple missions is the space shuttle's main engine; all other US rocket engines were designed for expendable launch vehicles. The SSME is a high-pressure, fuel-rich, staged combustion, rocket engine that has proved to be very good, however it took a tremendous amount of work to reach that status. Generally, each engine is fully inspected after every mission, which usually entails a complete disassembly and reassembly. The ORS mission requirements cannot be satisfied with that level of operations and maintenance. The poor operability of the SSME is a result of its ultra-high performance design—high efficiency and low weight. We must take the lessons from the SSME and use them intelligently to design the next generation of rocket engines.

Hydrogen engine development may also be important for responsive spacelift. It cannot be definitively ruled out for an ORS booster engine, and a hydrogen upper stage may be attractive for some applications. The Air Force currently relies on the RL-10 engine for upper stage propulsion on the Atlas and Delta vehicles. The RL-10 is an expendable engine that has proven to be very reliable. A reusable upper-stage engine with higher thrust may be needed for a future system, and state of the art technology and materials can be used to build upon the proven features of the RL-10 to provide it. During its Space Launch Initiative program, NASA's Marshall Space Flight Center managed the preliminary designs of two prototype fuel-rich, staged-combustion, hydrogen-fueled, booster engines: the Pratt and Whitney COBRA engine and the Boeing Rocketdyne RS-83 engine. These engines use slightly different flow paths than the SSME; the fundamental objective of their design was to address the SSME's life, reliability, and operations and maintenance cost issues. Although both engines held promise, NASA had to stop their development because of budgetary constraints. While their development was not completely without risk, there were no significant technology obstacles identified for either engine since the fundamental operation and environment of a hydrogen staged combustion cycle engine is understood.

The oxidizer-rich, staged-combustion (ORSC), oxygen/RP-1 rocket engine is one of the greatest technical challenges for an ORS system. The United States has never developed such an engine, during early rocket engine development of the fifties and sixties, the US headed down an evolutionary path of continual improvement and increasing size with gas generator engines. However, the Soviet Union chose a evolutionary path of development with staged-combustion engines. The Soviet Union developed a large ORSC engine for it's space shuttle, the RD-170, and modified that engine for sale to the United States for the Atlas III and Atlas V launch vehicles, the RD-180. Although it is a good engine, the RD-180 was designed and produced in Russia, with some support from a US based partnership, and does not meet the operability and long-life requirements for an ORS system.⁷ It is not known what modifications to the RD-180 would be required to meet them.

When NASA stopped the COBRA and RS-83 projects in 2002, it did so based on the risk associated with the development of a hydrogen-fueled booster engine versus the risk associated with the development of a staged-combustion, kerosene-fueled, booster engine. Preliminary reusable-launch-vehicle concept studies also identified the need for an ORSC kerosene engine. The Marshal Space Flight Center managed studies for large ORSC liquid oxygen/RP-1 engines with two US aerospace contractors, Boeing and Northrop Grumman. In June 2003 Boeing Rocketdyne completed the preliminary design of a one-million-pound thrust engine, the RS-84. The RS-84 engine is a risk reduction prototype engine that will verify the design and fabrication of an ORSC engine for high reliability and long life. The RS-84 is designed specifically to address the lessons identified from operating the SSME and includes new design approaches, materials, and processes to increase safety. The Northrop Grumman Space Technology TR-107 one-million-pound thrust ORSC engine concept is less mature than the RS-84 due to NASA's funding limitations and because it also uses new design approaches, materials and processes to provide a safe and reliable booster engine. Since the United States has no direct experience with kerosene-fueled, staged-combustion engines, we may encounter unknown issues with its operation and operational environment. The development and testing of prototype engines are essential to reducing the risk for an operationally responsive spacelift vehicle.

Aero-structural Challenges

The *Columbia* Accident Investigation Board (CAIB) determined that the probable cause of the space shuttle *Columbia* accident was foam falling from the external tank hitting and damaging the wing's leading edge, which allowed the hot plasma generated during reentry to enter the wing. The hot plasma caused the inner aluminum structure of the wing to fail, leading to the aerodynamic break-up of the vehicle.⁸ The public has also become more aware of the continuous maintenance problems associated with the tiles of the Space shuttle's thermal protection system since the accident.⁹ The development of a more robust and operable thermal protection system for reusable spacecraft has been underway for some time and was incorporated on each of NASA's recent X-vehicles, the X-33 and X-34. However, neither of these systems were completed or flight tested. Any new reusable launch vehicle will require an integrated aerodynamic structural system that can provide long life without significant maintenance. For an ORS RLV, the specific design will determine what type of advanced thermal protection and structural systems are appropriate.

The space shuttle's external tank contains the liquid hydrogen and liquid oxygen for the main engines, but is not recovered for reuse. The tank is constructed of an advanced aluminum alloy that is machined, rolled into shape, and welded. Polystyrene foam is sprayed onto the tanks for insulation. These tanks were not designed for reuse and significant design changes would be necessary before they could meet ORS system reusability requirements.

Propellant tanks must be developed that can safely and repeatedly withstand the intense loads from operations at the low temperatures of the cryogenic propellants, the forces generated during launch, and the higher temperatures encountered during reentry. For structural-mass efficiency, the design of the propellant tanks must be integral with the vehicle structural design, and the tanks may be designed to carry a substantial part of the vehicle load in ways that previous tanks have not been designed. Composite structures are now widely used in military aircraft designs because of their strength advantages. Likewise, composite tanks have been a major area of research within the last decade also due to the potential strength advantage of graphite and carbon fiber composite structures. For ambient temperature liquids, such as kerosene-based RP-1, composite tanks technology is relatively well understood and little development is needed. However, composite tanks still need significant development before they will be suitable for cryogenic liquids such as liquid oxygen and liquid hydrogen. The X-33 conformal composite liquid hydrogen fuel tank failed during testing due to flaws introduced during the fabrication process. To date, most composite liquid oxygen tanks have used metallic liners because of the incompatibility of oxygen and the epoxy material. Further technology work is needed for metallic lined composite tanks, and for composite designs that can safely avoid the use of metallic liners. Since composite materials are extremely sensitive to fabrication processes, further development of the technology used in those manufacturing process is also needed.

Thermal management of the aerodynamic structural system is a critical technology area in the development of highly operable reusable launch vehicles. For rocket-based vehicles, the primary thermal requirement is designed around the atmospheric reentry heating portion of the flight.¹⁰ Concepts based on air-breathing vehicles must design for the significant aerodynamic heating that is encountered both during the high-Mach ascent and the atmospheric reentry. The vehicle's structural design must be able to withstand hot temperatures or have an aerodynamic surface design that prevents the structure from getting hot by using passive and/or active thermal protection systems. A technology development has been proposed for an integral structure based on a high-temperature, metallic-alloy, honeycomb-type structure. Reinforced carbon-carbon (RCC) structures have been in use on the space shuttle since 1981 and are very good materials for the high temperature environment of leading edges. The damage caused to the space shuttle RCC during the CAIB testing, shown in figure 10, demonstrates the relative intolerance of the material to high-energy impact. Obviously, additional technology development and alternatives are needed for RCC thermal protection aerodynamic surface systems. Passive or actively cooled ceramic matrix composite materials have also shown sufficient potential to warrant additional development.

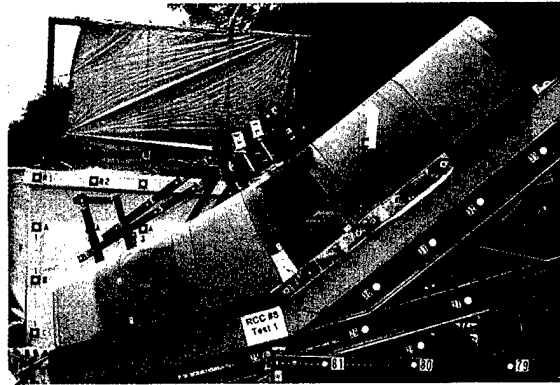


Figure 10. CAIB testing of RCC wing panel, courtesy of the *Columbia* Accident Investigation Board website, <http://www.caib.us/photos/>

Thermal protection systems that cover large areas of the vehicle surface, also need significant improvement. Figure 11 shows the materials used in various regions of the space shuttle orbiters. The fourth sample is of the high temperature tiles on the windward (bottom) side of the orbiter. Each orbiter has thousands of these tiles, and each tile is custom for its position on the vehicle, and the tile system has been a maintenance problem from the first flight. The first three samples in figure 11 are insulation from lower temperature areas of the orbiter.

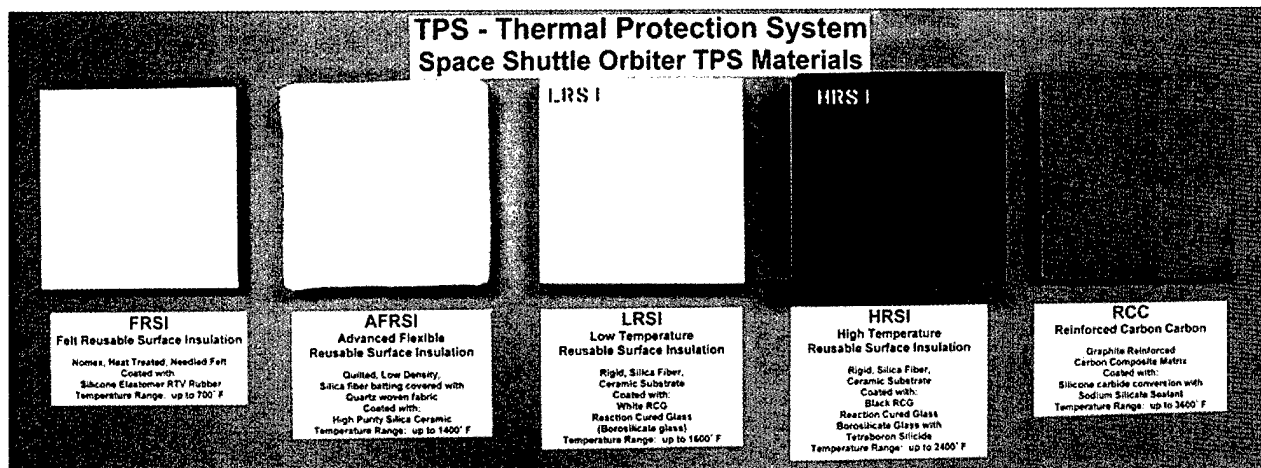


Figure 11. Space shuttle thermal protection system materials, courtesy of the CAIB website.

Avionics Challenges

The two primary technical challenges that exist in the area of a responsive launch vehicle avionics are (1) avionics hardware and software for autonomous vehicle operations and (2) integrated vehicle management systems. With the recent advances in electronic and computer technologies in the commercial world, there are few significant hardware areas of concern. The problem is primarily a detailed integration of electronic systems. Although the recent and successful use of unmanned aerial vehicles—under autonomous or remote

control—has demonstrated their ability to function, a spacelift system traveling at 26,000 feet per second is a significantly different problem.

Integrated vehicle health management (IVHM) systems that monitor vehicle and subsystem health will be critical to operationally responsive spacelift. These management systems will have two critical roles. The identification of an impending failure and the initiation of real-time mitigation actions to put the vehicle or subsystem in a more failure avoidance benign environment is the system's first necessary task. The secondary role is to continually monitor the vehicle or subsystem performance and identify trends indicating that a maintenance action or an inspection is needed. A propulsion system example of such monitoring would be the detection of an anomalous vibration from a turbo pump. The engine health management system would notify the integrated vehicle health management system of the potential failure mode, and recommend that the engine be throttled to a low power level. The IVHM would determine if a lower power level would be acceptable; if not, it would determine whether the output of other engines could be increased; and, if so, would issue the appropriate commands to the engines. The IVHM then makes a log entry that the turbo pump on that particular engine needs maintenance, and schedules the necessary maintenance before the vehicle returns to base. The primary technology challenge for the IVHM systems is the development of robust instrumentation and the development of algorithms to intelligently act upon the data provided by the sensors. IVHM and major subsystem health management systems have been slow to enter the space shuttle fleet due to concerns that false failure indications, or confounding sensor indications would cause more risk than the current mode of operation.

Mechanical and Electrical Challenges

Hydraulic systems on the NASA space shuttles are one of the primary causes of poor operability. Hydraulic systems provide the power by which the main engine thrust vector and the aerodynamic flight surfaces are controlled. Great care must be exercised to avoid any contamination of the hydraulic systems that could lead to faulty operation or cause failures. Hydraulic systems are also prone to leakage, so inspection and maintenance must be continually performed to ensure the hydraulic system is leak free and operates properly. Hydraulic fluid can also contaminate other systems and could present a flight hazard. The substitution of electric for hydraulic control systems could potentially help improve a launch vehicle's operability.

A technology precedence exists as commercial and military aircraft have recently been built using electrically operated flight control systems, in place of hydraulic ones. An all-electric launch vehicle will require a more capable power system whose requirements will be determined by a specific launch vehicle trade study, determining whether auxiliary power units (APUs), fuel cells, batteries, or some combination is needed. Over the last decade, significant progress has been made in battery and fuel cell technology to support environment-friendly automobiles. APUs are used when more power is needed than can be supplied with batteries. Aircraft APUs usually use gas turbine engines to drive generators, they are not feasible for launch vehicles. The space shuttle, its solid rocket boosters, and even F-16 fighters use hydrazine fuel driven APUs. However, the hazards and operational constraints associated with hydrazine make it undesirable for use in a future system. Technology development is needed to increase the *specific power* (power produced per unit weight), storage efficiency, reliability and operability. Specifically,

technology development is needed for low maintenance, high power generation, high power management and distribution devices and lightweight low maintenance energy storage. Power production is the first half of the problem; the second half is converting that electrical energy into a mechanical effect.

Electro-mechanical actuators (EMA), electro-hydraulic actuators (EHA), and electro-pneumatic actuators (EPA) convert electrical energy into mechanical motion. Actuators are needed to control the thrust vector of the main engines during powered ascent, the aerodynamic control surfaces, and some propulsion system valves. EMAs consist of an electric motor and a series of gears to reduce the speed and increase the delivered torque. Electro-hydraulic actuators combine the benefits of an electric system with the benefits of hydraulic systems. EHAs use an electric motor to drive a hydraulic pump, and the hydraulic pressure acting on a cylinder provides the mechanical actuation energy. EPAs are similar, but instead of a hydraulic pump, a compressor builds pneumatic pressure. EHAs and EPAs avoid the operability issues associated with a central hydraulic/pneumatic supply and distribution system.

There is very little experience in the use of electrically operated actuators for rocket and launch vehicle systems. In some cases, the required force or torque is greater than that required for aircraft or ground actuators. In other applications, the rate at which the actuator must operate is greater than current systems provide. A launch vehicle is a closed system, and without introducing further complications, electrical systems can quickly get hot. During operation in an aircraft, the duty cycle (amount of time between operation) of an EMA is relatively long and the actuator has an opportunity to dissipate heat to its environment. The requirement for high power, high temperature, and fast-acting actuators necessitates technology development.

Operations and Payload Challenges

To achieve the desired responsiveness, vehicle and fleet operations must be developed in conjunction with the vehicle concept, and the vehicle concept must be iterated to accommodate enhanced operations. All aspects of operations, from premission planning to post-mission assessment must be made more efficient. The flexibility to accomplish multiple types of missions complicates planning, however most of the tools, processes, and systems needed for planning and assessment do not need technology development. Using state of the art systems as a point of departure, most of these systems can be developed. Improved real-time weather prediction and integrated launch range management are areas that need to be initiated soon. Technology development is needed for automated vehicle umbilical conduits for power, data, and propellants to decrease launch preparation time and increase safety and reliability.

A highly responsive launch vehicle serves no purpose and is over-designed if it has to wait for the payload to be integrated, calibrated, and readied for launch. The development of operationally responsive payloads and satellites may require a paradigm shift to a philosophy that embraces many small, short-life satellites that individually are less capable but when operated as a network, provide enhanced effects. Technology development may be needed to ensure these types of satellites are available when needed. Global strike missions using common aero vehicles will provide the United States a space force application capability for conventional or kinetic-energy precision weapons. Once the payload is available, integration, calibration, and

checkout can require a considerable amount of time. The evolved expendable launch vehicles have made considerable progress in this area, however it still takes on the order of months. When responsive satellites are designed using standard interfaces, the development of automated calibration and checkout systems will become cost effective.

Notes

1. Specific power is the power produced by the engine divided by its weight.
2. Hydrogen storage and distribution systems must use vacuum jacket insulation systems, the same concept as thermos bottles, these systems are expensive to install and maintain.
3. Based upon FY03 liquid oxygen and liquid hydrogen cost at Stennis Space Center, MS where the hydrogen is transported by barge a relatively short distance from the production facility. Transportation to an inland CONUS base would substantially increase the cost. RP-1 cost of \$3/gal could actually decrease based upon a substantial increase in flight rate.
4. The exact ORS mission requirement have not yet been determined, it is not yet known if the mission turn-around time for a vehicle is hours or days. Early in the development of a system it is easy to over-specify requirements, to include capabilities or requirements that would be nice to have, but not essential.
5. A cryogenic liquid is one whose boiling point is below ambient temperature at the pressure it is being stored and liquids must be actively cooled due to the heat transfer through their tanks. On the other hand, a storable liquid propellant is one that can be stored as a liquid at ambient temperature without refrigeration.
6. The hydrogen peroxide for liquid rocket engines is not the same as used as a disinfectant, drug store hydrogen peroxide is 3% concentration, whereas the rocket engine variety is 90–98% concentration.
7. As part of the EELV program, domestic production of the RD-180 is planned.
8. See the Columbia Accident Investigation Board final report at <http://www.caib.us/> for additional information about the Space Shuttle Columbia accident.
9. The CAIB final report discusses in depth the background and history of the Space Shuttle Orbiter's thermal protection system, and it's history of damage and maintenance.
10. During ascent of a launch vehicle with rocket propulsion, the vehicle climbs through the dense regions of atmosphere quickly, and doesn't need significant design for aerodynamic heating.

Chapter 5

The Way Ahead

What is the way ahead? Where is the United States military, and specifically the Air Force going with respect to responsive access to space? In the summer of 2002, the "National Space Policy Review," a National Security Presidential Directive, directed a review and possible update to the space policies that had been issued in 1996.¹ In the aftermath of the 11 September 2001 attacks, it was anticipated that an updated space policy would refocus space efforts away from supporting commercial development of space and NASA's role as the government lead for reusable launch vehicle development, to a policy focusing agencies on the development of space systems for national security.² Then, in the wake of the space shuttle *Columbia* accident in February 2003, the space policy review was put on hold. The Geyman Commission, as documented in the CAIB report, identified the lack of a national vision for space, as an issue that has prevented the agency from developing significant advances in space transportation.³ In January 2004, President George W. Bush issued "A Renewed Spirit of Discovery," his vision for US Space Exploration, and stated, "The fundamental goal of this vision is to advance US scientific, security, and economic interests through a robust space exploration program."⁴ While the areas of the vision gaining the most public attention are the return to the Moon, at first robotically and then with a permanent human presence, followed by the exploration of Mars, the inclusion of "security" in the goal statement is probably a glimpse into an upcoming revision of the National Space Policy.

The National Space Policy revision should be expected during the spring or summer of 2004, and may have a three-prong approach. First, the policy will probably call for the development of space systems to support national security and national economic interests. Secondly, it will support the "renewed spirit of discovery" and space exploration. The final focus may be on using commercial space systems to the greatest extent possible. Unlike the 1996 policy, the revision will probably not assign specific roles to specific agencies, rather it will let the programs evolve based upon their requirements. Unfortunately, this type of policy leads to a divergence of vehicles and systems to support responsive access to space for national security, versus vehicles to support the civil exploration of space. However, the common thread will remain technology development. Much synergy is possible in the areas of propulsion, airframes, avionics, power systems, integrated health management, and operations that will reduce the net government investment and sustaining costs.

Since 2003, the DOD's director of Defense Research and Engineering (DDR&E), has coordinated a multiagency effort entitled the National Aerospace Initiative (NAI). "NAI is a

partnership between the Department of Defense and National Aeronautics and Space Administration designed to sustain America's aerospace leadership through technology development and demonstration in the three pillar areas of high-speed/hypersonics, space access, and space technology."⁵ The Air Force portions of the activity are being led by AFRL with substantial involvement by AFSPC. NASA has been involved through the NGLT program, and is responsible for developing and maintaining the Integrated Space Transportation Plan (ISTP), which documents the current and future plans for civil access to space and in-space for exploration missions. The integration of NASA's ISTP with DOD's access-to-space plans should evolve into a national space access plan. Planning and communication will help eliminate or reduce redundant activities—a responsible way to spend taxpayer dollars. While the NAI does not have funding and program management responsibility for any of the individual programs, it serves as a coordinator and consolidates information about technology risks and risk mitigation activities.

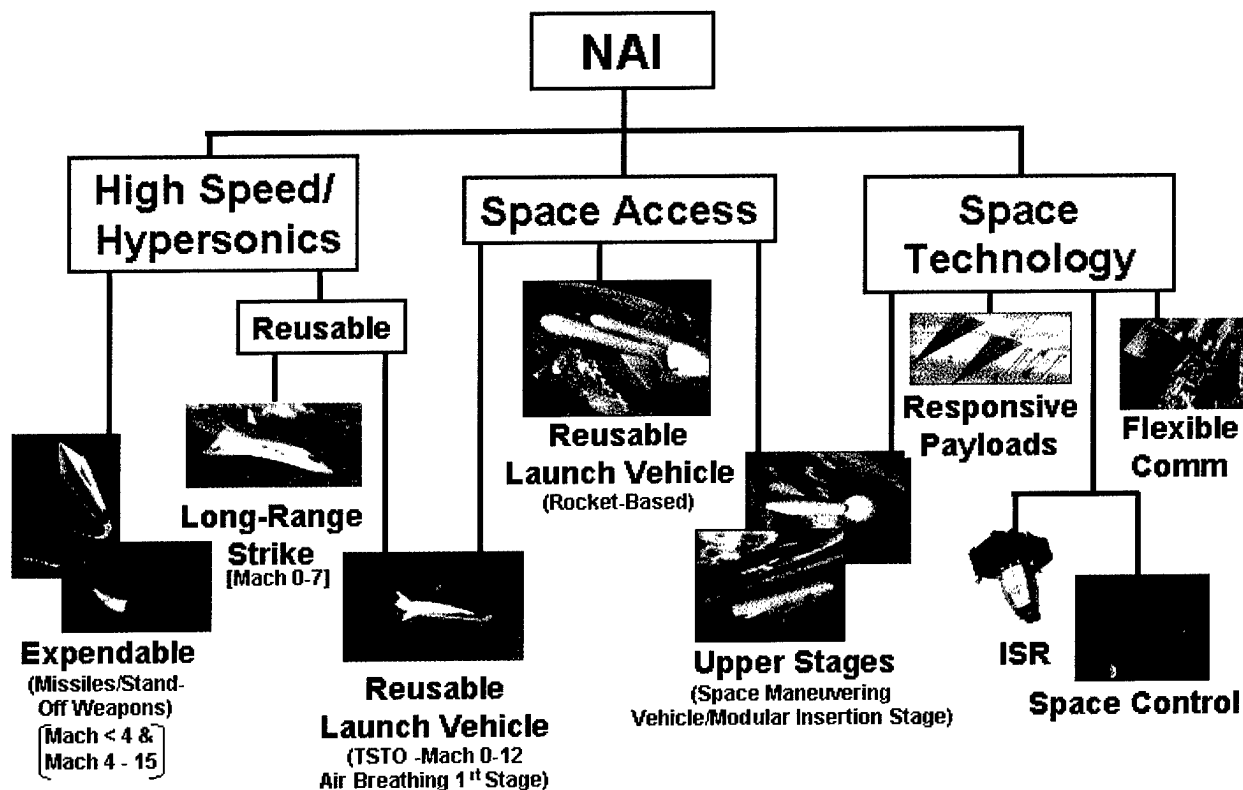


Figure 12. Three-pillars of the National Aerospace Initiative

All three NAI pillars in figure 12 provide enabling or supporting capabilities for the other legs.⁶ NAI can identify the technology developments essential for each objective through the goals, objectives, technical challenges, and approaches (GOTChA) planning and execution process and by synergizing resources across the services and other agencies, particularly the Air Force laboratories and NASA. As the basic technologies are matured, system development will

diverge into two paths: a military path to support ORS or the military space plane concept, and a civilian path to support NASA's research and exploration missions.

NAI is using a three-tier approach to provide an initial operational capability (IOC), with near-term in the 2009 timeframe, mid-term on or about 2015, and far-term beginning around 2025. Definitive time phases provide hard deadlines against which programs can be developed, budget requirements inserted into the appropriate Program Objective Memorandums (POM), and the acquisition processes initiated. Simply because of the time required for the budget, contract, and procurement processes, there is little time to develop advanced technologies to support 2009 capabilities. The near-term capability may consist of demonstrator technologies or systems that demonstrate an increased operability based on current technologies. The goals established for each phase are aggressive and pull technology forward to achieve them. The readiness of each technology is evaluated at the end of each phase and a decision can then be made to: (1) pursue the full-scale development of an operational system based on those technologies, (2) leap over the early capability and continue technology development into the next phase, or (3) terminate that particular technology effort.

Notes

1. National Security Presidential Directive (NSPD)-15, "National Space Policy Review," 28 June 2002, http://www.ostp.gov/html/02_7_15_2.html.
2. White House Fact Sheet, "National Space Policy," 19 September 1996, <http://www.ostp.gov/NSTC/html/pdd8.html>.
3. *Columbia Accident Investigation Board Report* (Washington, DC: National Aeronautics and Space Administration or Government Printing Office, 2003), vol. 1, <http://www.caib.us/news/report/volume1/>.
4. President George W. Bush, "A Renewed Spirit of Discovery: The President's Vision for US Space Exploration," January 2004, <http://www.ostp.gov/html/RenewedSpiritofDiscovery.pdf>.
5. Dr. Ronald Sega, director, Defense Research & Engineering, National Aerospace Initiative website home page, personal comments from <http://www.dod.mil/ddre/nai/>.
6. Jay McDaniel, AFRL Space and Missile Systems Sector, "An Overview Perspective of Space Propulsion within the United States Air Force," (unpublished presentation to the Space Propulsion Synergy Team, 21 May 2003).

Chapter 6

Conclusions

The development of an operationally responsive space system is technically feasible with current technology, however that near term solution would represent a system of systems that meets the mission needs by using the unique capabilities of existing systems, enhancement to current systems, and new capabilities to fill gaps. The affordability of such a system would be questionable. A system developed today would have to rely upon a large inventory of Evolved Expendable Launch Vehicles, the space shuttle, and/or modified ICBMs.¹ Obviously, this would be a complicated and expensive system. Although these heritage systems may play a role in responsive spacelift over the next ten to fifteen years, a new system is needed to truly meet the ORS requirements.

A responsive spacelift system that fulfills the space doctrine vision will depend on significant developments in the technologies that support launch vehicle systems and subsystems. The primary areas for those developments are liquid propulsion, advanced air-breathing propulsion, integrated long-life structures, and thermal protections systems. The alternative vehicle configuration concepts are developed sufficiently to indicate feasibility, the necessary technologies are defined for each concept, the technology requirements are then assessed for their current readiness level and their risks identified. This list of technologies and the commonality of required technologies between alternative vehicle concepts can be used to guide funding decisions. The interaction of Air Force research laboratory communities with NASA is a positive step that is vital to national interests. Leadership, through the NAI, should help define the nation's sustained technology development requirements, which, in turn, will support a future responsive spacelift system. The national program must remain flexible—as new technologies emerge and others fail to develop as expected—able to redirect efforts and resources.

A word of caution—technologists often focus on trying to build a better mousetrap when the objective is to catch a mouse. The balance of technology-push and technology-pull is essential. Too much technology-push will infuse the system with a dependence on the success of so many technology developments that its overall development will have excessive technological program risk. Too much technology-pull excessively depends on older, mature systems that are needlessly expensive and their cumulative costs add excessive budgetary program risks. Although this paper has not addressed specific operational responsive space mission requirements and rationale, those will result in an iterative process as some developing technologies mature and others fail—in much the same way the airplane evolved to have increased capabilities. Responsive space missions will evolve as technologies mature and enable enhanced capabilities.

Note

1. A solution that requires warehousing EELVs like cordwood is not realistic in today's budgetary environment. With seven Delta IV launches costing on the order of \$1 billion, a reusable launch vehicle fleet would be paid for a less than a year.

Glossary

°F	degrees Fahrenheit
ACES	air collection and enrichment system
AFRL	Air Force Research Laboratory
AFSPC	United States Air Force Space Command
AoA	analysis of alternatives
CAIB	<i>Columbia</i> Accident Investigation Board
CAV	common aero vVehicle
CONOPS	concept of operations
CONUS	continental United States
CRL	capability readiness level
DARPA	Defense Advanced Research Project Agency
DDR&E	Defense Research and Engineering
EELV	evolved expendable launch vehicle
EHA	electro-hydraulic actuator
EMA	electro-mechanical actuators
EPA	electro-pneumatic actuator
ET	external tank
EWO	emergency war order
FA	force application
FALCON	Force Application and Launch from CONUS
GOTChA	goals, objectives, technical challenges, approaches
GPS	global positioning system
HTHL	horizontal takeoff, horizontal landing
IOC	initial operating capability
ISR	intelligence, surveillance, and reconnaissance
ISTP	integrated space transportation plan
IVHM	integrated vehicle health management
LEO	low earth orbit
MNS	mission needs statement
MRL	materials readiness level
MSFC	Marshall Space Flight Center
MUA	military utility analysis
NAI	national aerospace initiative
NASA	National Aeronautics and Space Administration
NGLT	next generation launch technology
nm	nautical mile
OCS	offensive counterspace
ORS	operationally responsive spacelift (initial use)

ORS	operationally responsive space (expanded and final use)
ORSC	oxidizer-rich staged combustion
OSP	orbital space plane
POM	program objective memorandum
PRL	process readiness level
psi	pounds per square inch
RBCC	rocket-based combined cycle
RCC	reinforced carbon-carbon
RLV	reusable launch vehicle
RP-1	Rocket Propellant-1
SAC	Strategic Air Command
SSME	space shuttle main engines
SSTO	single-stage-to-orbit
TBCC	turbine-based combined cycle
TPS	thermal protection system
TRL	technology readiness level
TSTO	two-stage-to-orbit
VTHL	vertical takeoff, horizontal landing

Biographical Sketch

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